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Equipment and Theory

A lesson from THERMAL SPRAY TECHNOLOGY

by
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Course 51
Lesson, Test 2

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MATERIALS ENGINEERING INSTITUTE

Metric Conversion Factors

To convert from	To	Multiply by
in.	mm	25.4
in.	m	25.4×10^{-3}
mil	µm	25.4
µin.	µm	25.4×10^{-3}
in.^{2}	m^2	6.45×10^{-4}
in.^{3}	m^3	1.64×10^{-5}
ft.	m	3.048×10^{-1}
ft.^{2}	m^2	9.29×10^{-2}
ft.^{3}	m^3	2.831×10^{-2}
oz.	g	2.834×10^{1}
lb.	kg	4.536×10^{-1}
Btu	J	1.054×10^{3}
Btu/lb. • °F	J/kg • K	4.18×10^{3}
Btu/ft. • hr • °F	W/m • K	1.730
10 in./in./°F	10^{-6} mm/mm/°C	1.8
psi	Pa	6.895×10^{3}
psi	kPa	6.895
ksi	kPa	6.895×10^{3}
ksi	MPa	6.895
ksi • in.$^{1/2}$	MPa • m$^{1/2}$	1.099
ksi$\sqrt{\text{in.}}$	MPa • $\sqrt{\text{m}}$	1.099
oz.f	gf	28.4
lbf	kgf	4.536×10^{-1}
lbf	N	4.448
lbf • ft.	N • m (or J)	1.356
lbf/in.^{2}	kgf/cm^2	14.223
lbf/in.^{3}	kgf/m^3	2.768×10^{4}
lb./ft.^{3}	kg/m^3	16.019
lb./in.^{3}	g/cm^3	2.768×10^{1}
lb./in.^{3}	kg/m^3	2.768×10^{4}
gal (U.S. liquid)	L	3.785
gal (U.S. liquid)	m^3	3.785×10^{-3}
lb./gal	g/L	119.826
ft./gal	ml/L	748
°F	°C	(°F – 32)/1.8
°F	K	(°F + 459.67)/1.8
°C	°F	(°C • 1.8) + 32
°C	K	°C + 273.15
K	°C	°C – 273.15

Multiple and Submultiple Units

10^{18}	exa (E)	10^{-1}	deci (d)
10^{15}	peta (P)	10^{-2}	centi (c)
10^{12}	tera (T)	10^{-3}	milli (m)
10^{9}	giga (G)	10^{-6}	micro (µ)
10^{6}	mega (M)	10^{-9}	nano (n)
10^{3}	kilo (k)	10^{-12}	pico (p)
10^{2}	hecto (h)	10^{-15}	femto (f)
10^{1}	deka (da)	10^{-18}	atto (a)

Abbreviations

J	joule	m	meter	Pa	pascal
kgf	kilogram force	mm	millimeter	K	kelvin
L	liter	N	newton	W	watt

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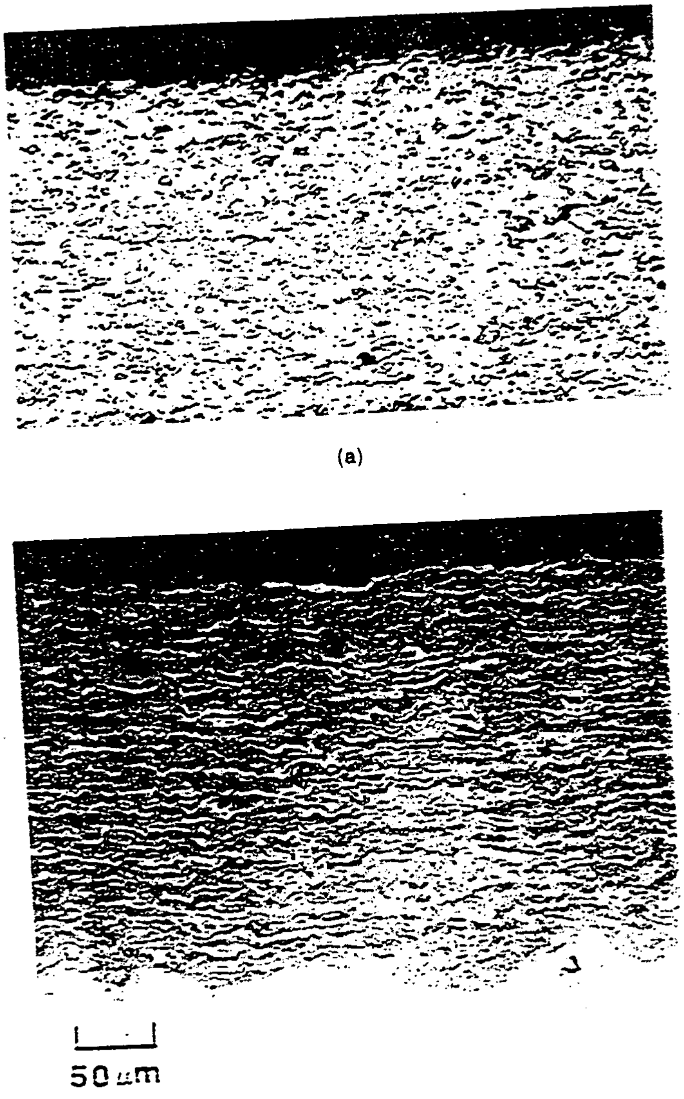
duces some of thermal spray industry's densest and highest bond-strength coatings. A large number of commercial aircraft engine wear coatings specify the process. It has also been shown that a higher degree of retained carbides found in D-Gun cermet (carbide) coatings, when compared to flame and plasma spray coatings, contribute to the D-Gun coating's higher hardness values. The higher retained carbide is due again to reduced oxidizing atmosphere of the D-Gun confined combustion zone which retain a high partial pressure of carbon in the atmosphere.

High-Velocity Oxyfuel Spray (HVOF)

Process. The high-velocity oxyfuel (HVOF) spray process was invented in 1958 by Smith et al. of Union Carbide, and commercially introduced in 1974 by Browning. The HVOF spray process is similar to the D-Gun process, with internal, confine combustion; however, the combustion gases are fed and combusted continuously. Gases include oxygen in combination with fuels such as propylene (C_3H_6), hydrogen, MAP, propane, and even liquid fuels such as kerosene. HVOF guns have combustor sections (air or water cooled) which combusts the fuel/oxygen mixtures under pressure and accelerates the combusted gas streams down a confined, cooled tube. Powders, with carrier gases, are fed into the nozzle where the particles are entrained with the confined, high-pressure combusting gases.



(a)

(b)

Figure 19. Typical D-Gun coating microstructures. (a) WC/Co and (b) $Al_2O_3 + TiO_2$ (Courtesy, Praxair)

The gun schematic in Figure 20 illustrates the basic HVOF features which incorporate an internal combustion, active gun cooling, particle injection into a tube with the high-pressure combusting gases, and a rapid supersonic nozzle expansion of the combusting gases. Particle heat transfer and efficiency and particle dwell times are increased by this design. HVOF's gas acceleration, higher than conventional combustion or even plasma, has also been shown to increase particle velocities with corresponding increases in coating density, coating adhesion, and with finer coating oxide inclusion distributions. Lower average particle temperatures, compared to plasma spray, likely reduces the degree of particle melting and oxidation. Yet despite the lower average particle temperatures, high coating densities are still achieved through HVOF's high particle impact velocities which easily deform particles that may not have been well melted.

Equipment. HVOF with the internal combustor requires active cooling systems and in addition has gas flow controls for much higher gas flow rates compared to conventional flame spray. These components are found to be important for managing HVOF's thermal input and for improving its control over the more conventional combustion processes.

Components. The key HVOF components are:

- Oxygen/fuel gas control mixtures (high flows);
- Powder injector;
- Powder gas flow control;
- Water circuit or air cooling;

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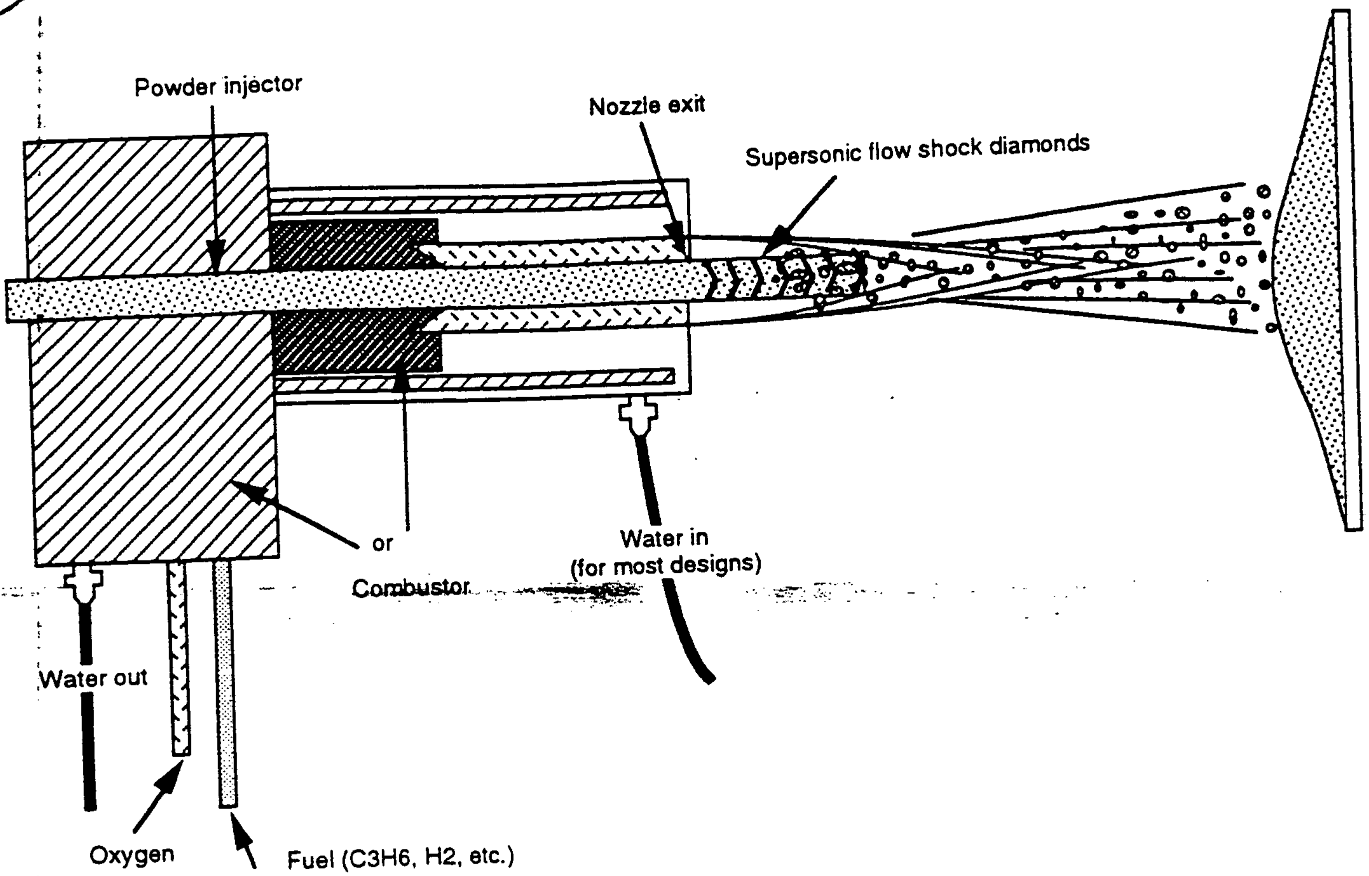

Figure 20. HVOF thermal spray gun.

- Nozzle cooling flow & control;
- Cooling passages;
- Nozzle tube/exit nozzle;
- Combustion gas injectors; and
- Fuel pumps (for liquid fuel systems).

HVOF equipment components differ further from conventional flame spray equipment by the added cooling, higher-pressure combustion gas delivery systems, and the powder delivery. The high gas flow rates and the criticality of combustion fuel mixtures require more precise gas flow systems; thus, rotometers have been replaced by high-flow-rate impact meters, critical flow orifices and/or mass flowmeter systems. The nozzle tube in combination with the combustor require the tubes/injectors to be cooled. Cooling in HVOF nozzles has been found to be critical in most devices for preventing the combustion products or molten/vaporized powder from depositing onto tube walls and for preventing tube thermal distress. Secondly, the high energy densities of HVOF torches put stress on components, increasing wear and creating component replacement needs not seen in the conventional flame spray processes. Thus, in the water-cooled designs, coolant temperature and flow-control feedback are necessary for obtaining consistent deposition quality. Finally, powder delivery and combustion gas injection is more precise in HVOF than in conventional flame spray in order to better control the thermal input to the distribution of powder particles.

HVOF spray coating processes are separated into four major designs: 1) internal combustion with the hot gases directed into a chamber where it mixes with and heats a mixture of carrier gas and powder particles; 2) simultaneous injection of powder into a combustion chamber where the mixture continuously burns and heats the particles; 3) confined combustion into which a stream of powder with carrier gas is injected; and 4) high-pressure liquid fuel systems with radial injection of powders downstream of the combustor exit. Figure 21 illustrates these various designs, showing the major differences between them; compare to the D-Gun process shown in Figure 18. Common to all HVOF methods is that the gases

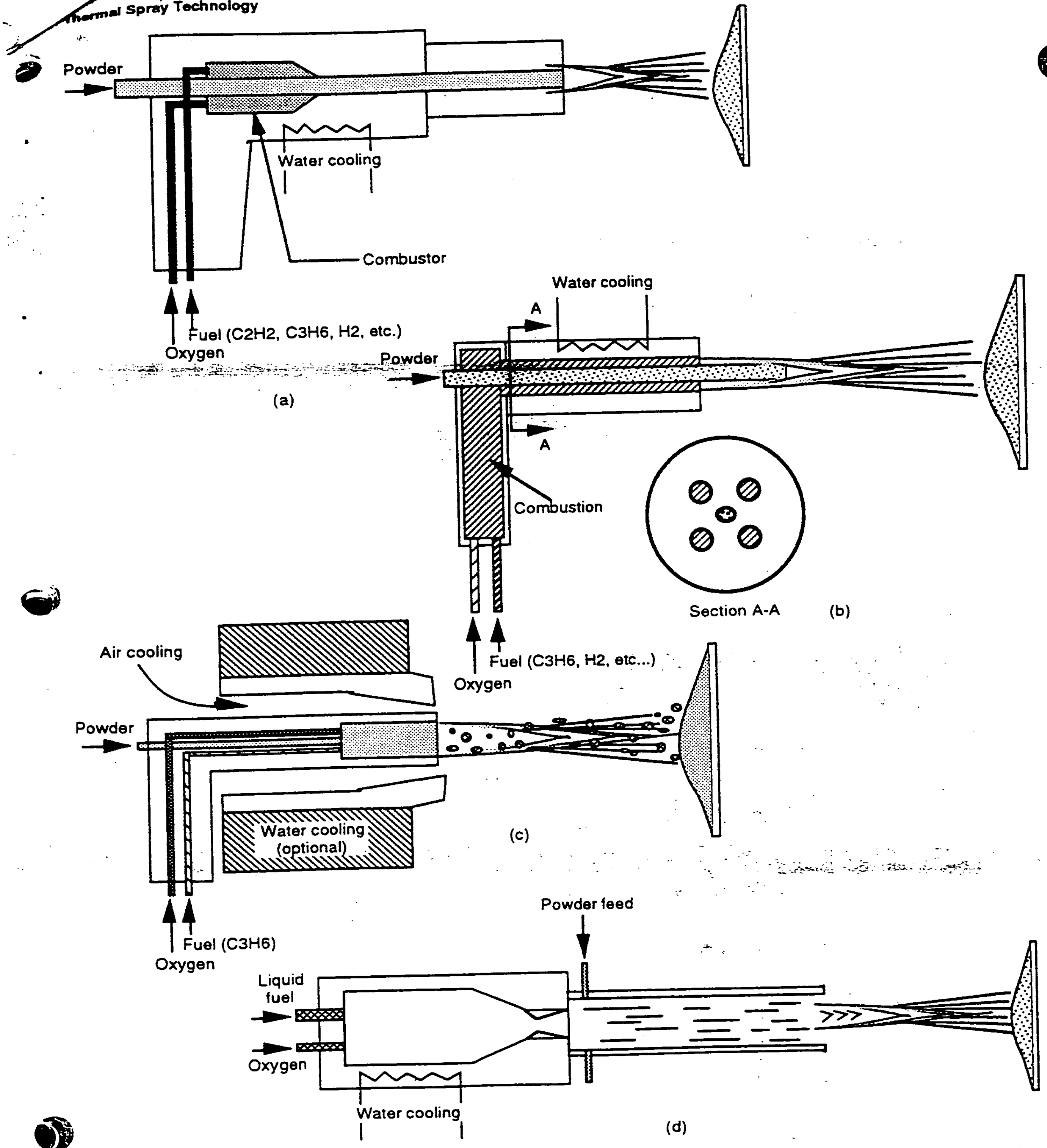

Figure 21. Operational principles of several commercially available HVOF thermal spray guns. (a) Top Gun®/CDS®, etc., (b) Jet Kote®. (c) Diamond Jet (D-J®) and (d) J-P 5000®.

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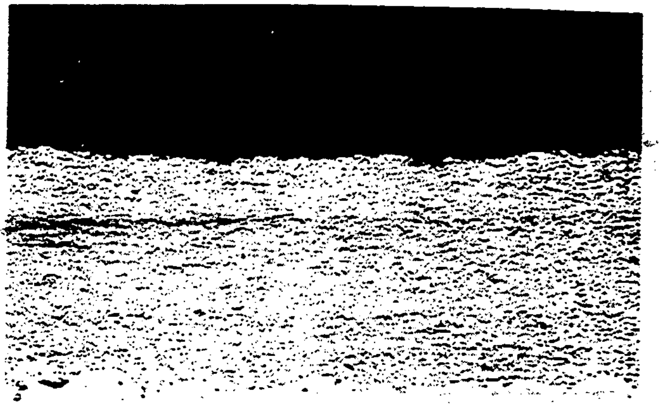
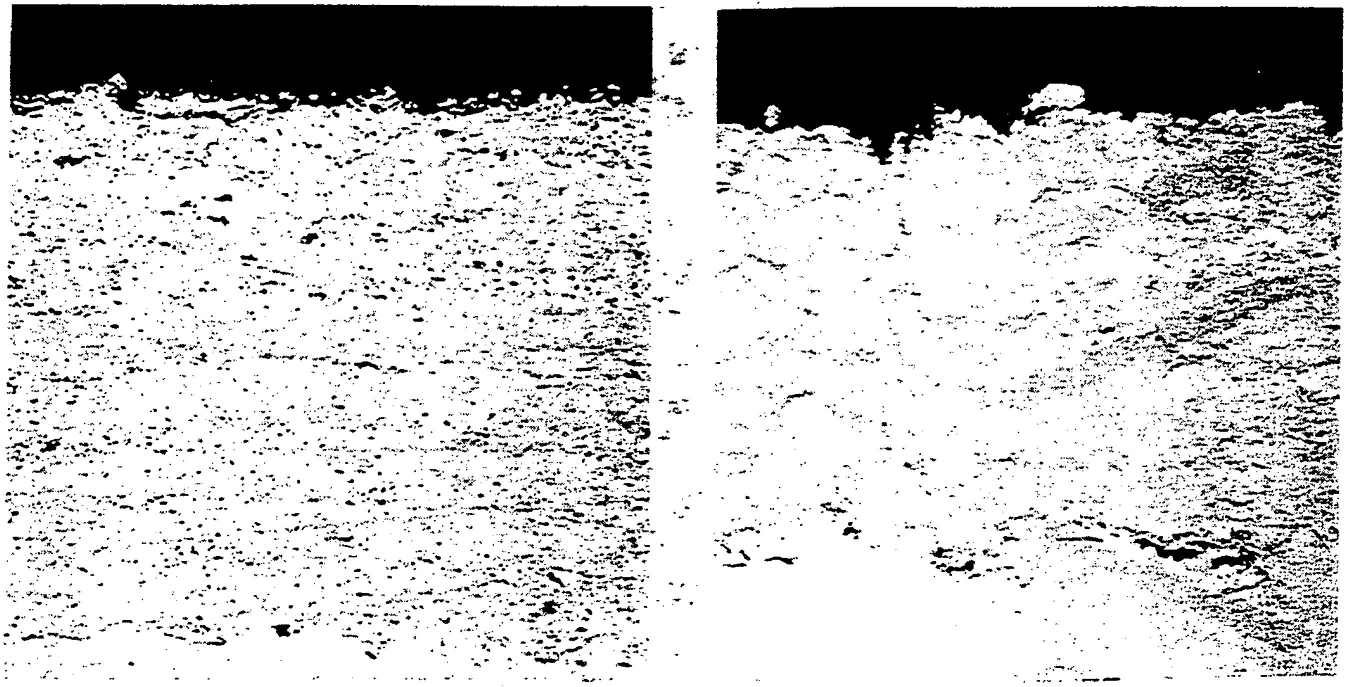
are being burned under higher-than-atmospheric pressures with the combustion gases, carrier gas, and an entrained distribution of powders being accelerated in the tube. The length of the nozzle, the design of heating chambers, the geometry/location of powder feed, and the cooling, either by water or air, are the major features which differ.



(a)

High nozzle gas flows, typically 150 to 300 slm (320 to 640 scfh) of oxygen and 200 to 600 slm (430 to 1280 scfh) of fuel gases, are typically fed into devices which all have supersonic expansion. The high velocity, high density gas flows accelerate the gases and powder particles to velocities much closer to the gas velocity compared to other thermal spray processes. The gas exit velocities are so high that most HVOF processes have noticeable, multiple "shock" diamond-shaped patterns in the gas jets which is denote rapid gas density changes in the luminous jets structures, indicating the supersonic nature of the exit gas velocities. The number of shock diamonds, although related to gas velocity, is not directly an indication of Mach number (gas velocity relative to velocity of sound). Investigators have calculated and, in some cases measured gas exit velocities from Mach 1 to Mach 2, which for the given gas and temperatures in HVOF spraying, is approximately 1000 m/s (3280 ft./s).

Deposit Characteristics. Reportedly, the HVOF coating structure and hardness values are comparable to D-Gun coatings. HVOF-sprayed coating density, adherence and oxide content and compare



(b) (c)

Figure 22. Typical microstructures of HVOF sprayed coatings. (a) WC/Co, (b) Cr$_3$C$_2$/NiCr carbide and (c) 316 stainless steel. (Courtesy, Metco, Hobart Tafa Technologies and Miller Thermal, respectively)

favorably with many plasma-sprayed coatings. Supersonic acceleration of combustion gas/particle mixtures has added new capability and is offering new opportunities for combustion spraying. HVOF coating bond strengths have been reported over 83 MPa (12 ksi), and coating densities over 98% are reported for materials such as WC/Co and many metals. Compositional analysis of WC/Co coatings show that, compared to plasma spray, only a small degree of WC decomposition has occurred, thus preserving the material's intrinsic hardness values. Table 1 summarized HVOF's attributes, including the higher particle velocities and the lower heating temperatures of HVOF compared to plasma spray. These HVOF features are mainly responsible for the lower degree of WC decomposition.

Figure 22 shows some examples of HVOF coating microstructures, showing the finer oxide dispersions, denser and finer splat structures, and the high carbide retention. The excellent bonding, high coating densities, and the homogeneous coating structures of HVOF-sprayed coatings is now renewing commercial interest in combustion spray methods. HVOF appears to be a high growth area and many applications are now reconsidering combustion spray processes in preference to plasma spray and the proprietary D-Gun spray processes.

Wire-Arc Spray

Process. Wire-arc spray processes utilize the DC electric arc to directly melt consumable electrode wires, as schematically shown in Figure 23. Unlike the other thermal spay processes which indirectly heat the particles through heated gas jets. Thus the thermal efficiency of the wire-arc spray is higher than that of all the thermal spray processes. In wire-arc spraying, electric current is carried by two electrically conductive, consumable wires with an electric arc forming between the wire tips in the gap where the two wires are continuously being converged. A high-velocity air jet blowing from behind the moving wires strips away the molten metal which continuously forms as the wires are melted by the electric arc. The high-velocity air jet flow ranges from 300 to 3,000 slm (40 to 410 scfh). It breaks up or atomizes the molten metal into finer particles in order to create a fine distribution of molten metal droplets. The atomizing air then accelerates the particles away from the electrode tips to the substrate surface where the molten particles impact the substrate to incrementally form a coating. Note: unlike combustion or plasma spraying, the droplets are already molten when the material enters the jet, and are being continuously cooled by the atomizing air as the particles leave the arc zone. Thus, the optimized wire-arc spray process attempts to shorten the time of flight in order that the air jet cooling effects on the

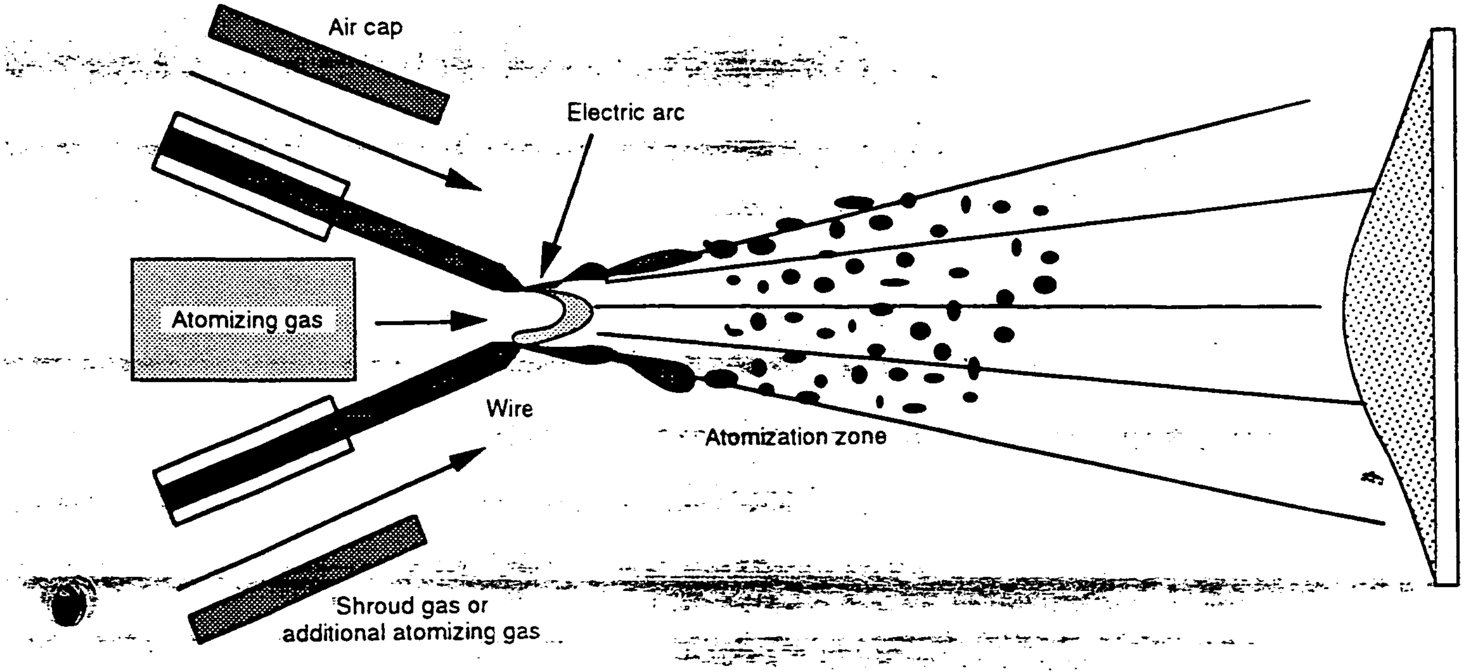


Figure 23. Operational principles of a two-wire-arc spray device.

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